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## I. The Radium Content of the Keweenawan Basalts and Some Accessory Minerals.

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By Wm. D. Urry.

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4. Urry, Wm. D.—Radio Activity Measurements. I. The Radium Content of the Keweenawan Basalts and Some Accessory Minerals. II. The Occurrence of Radium, Uranium and Potassium in the Earth. pp. 125–144. March, 1933. $0.50.

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By Wm. D. Urry.

# RADIOACTIVITY MEASUREMENTS.

## I. The Radium Content of the Keweenawan Basalts and Some Accessory Minerals.

By Wm. D. Urry.[1]

In determining the age of the Keweenawan Basalts in the copper mines of the Upper Peninsula, Keweenaw Point, Michigan, a series of accurate measurements on the radium content was carried out. In so far as the data required to calculate the age, namely, the helium radium and thorium content of these rocks, is not yet completed, the thorium remaining to be determined, it is not proposed to discuss the question of the geological age here but rather to give the results of the analyses for radium since these values also have an important bearing in other researches.

The field work was carried out by the author in July, 1931, thus ensuring an exact knowledge of the position and relation of the samples, most of which were obtained underground at that time.[2] The determination of the radium content was made in co-operation with Professor Dr. F. Paneth in his private laboratory in Koenigsberg. i. Pr. using the same emanation method as described by Paneth and Koeck,[3] and employed by them to determine the very small quantities of radium in the iron meteorites.

In Keweenawan times many hundreds of basaltic flows were laid down interspersed with strata of felsitic conglomerate and sandstone. These flows are of the "Plateau" type. The accompanying diagrams are included to facilitate the comprehension of the following data. Figure 1 shows very roughly the stratigraphical arrangement taking a cross section of the Keweenaw Point on a line about North-West and South-East. The oldest flows are those nearest the Keweenaw Fault and the youngest those nearest the Freda sandstone. The thicker lines represent very roughly the relative positions of the mines

[1] Contribution from the Johns Hopkins University, Baltimore, Md.

[2] The author is greatly indebted to the officials of the various mines and the staff of the Michigan College of Mining and Technology for their aid in collecting the specimens and instruction in the detailed geological aspect of the district.

[3] F. Paneth and W. Koeck, Zeit. Physik. Chemie. Bodenstein-Festband. 145 (1931). The standard solution was obtained from Prof. W. Bothe, of the Physikalisch-Technischen Reichsanstalt, Charlottenburg.

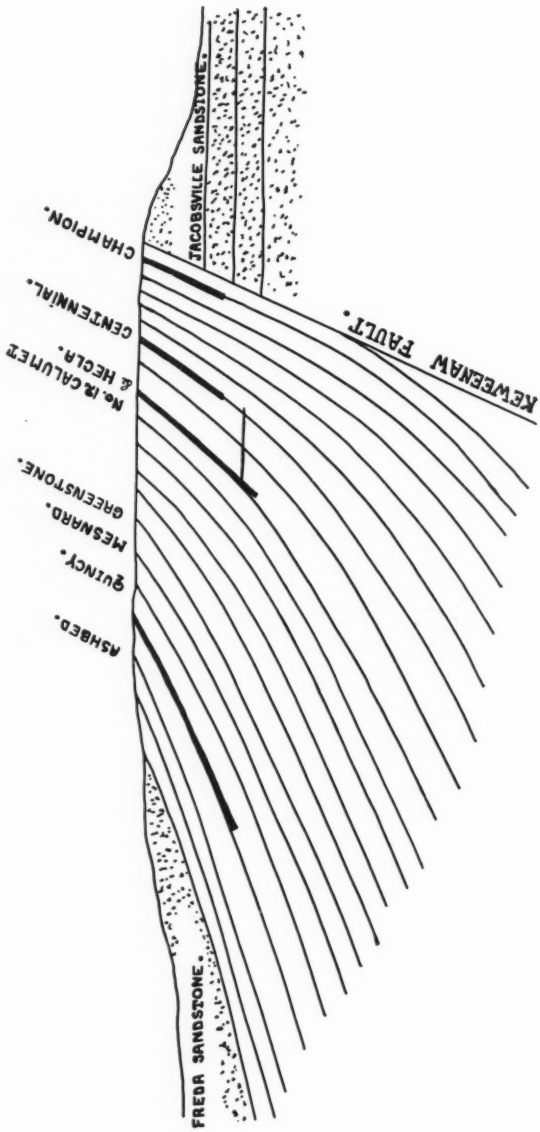


FIG. 1.—Cross-section sketch of the Keweenaw Point, Michigan.

although they naturally do not all fall on such a cross section but are spaced over many miles along the "Strike."[4] The beds on Keweenaw Point now dip with varying angles to the horizon ranging from 80° in the lower beds to 10° at some points in the later flows. Except where vertical, the mine shafts follow the angle of dip. This is explained by reference to Figure 2, an enlarged cross section of the flows. As a lava is laid down, gas bubbles rise to the top and some are entrapped in the solidifying lava, forming a permeable top to the flow. It is here that the mineralizing solutions have deposited along with several other types of minerals, the native copper. Hence the mine shafts follow the so-called "Amygdaloid lode" downwards and the levels or drifts follow the amygdaloid outwards in the horizontal direction. If the mine shaft is sunk in the amygdaloid in flow A, then flow B is termed the hanging trap to this lode and the portion of flow A underlying its amygdaloid, the foot trap. It will at once be seen that there is no geological stratigraphical difference between the lode and the foot trap, both being the same flow, although the term foot trap continues to be used in the district. The hanging trap, however, constitutes the flow directly above that in which the shaft or level occurs and must, therefore, be treated as a separate entity. As will be noted, most of the samples investigated are from hanging traps, that is, from the bottom of flows immediately overlying the flow being worked. In some cases a cross cut is run to reach another lode and this is also shown in Figure 2 to demonstrate roughly the positions of specimens Nos. 19 and 20. A conglomerate occurs where there was time for deposition between successive flows which need not be long. Forty-three samples in all were taken, twenty-three of which have been analyzed. The results are tabulated in the following order:

1. Basaltic and Felsitic flows.
2. Accessory minerals.

The flows are further subdivided into:

A. Early Keweenawan flows as represented by the Champion mine specimens.
B. Middle Keweenawan flows as represented by the Calumet and Hecla mine specimens.

[4] Lane, A. C., The Geological Survey of Michigan, Ann. Report (1909).
A very full account of the geology of the district is given in "The Copper Deposits of Michigan," B. S. Butler and W. S. Burbank. Professional Paper 144, U. S. Geological Survey, Washington (1929).

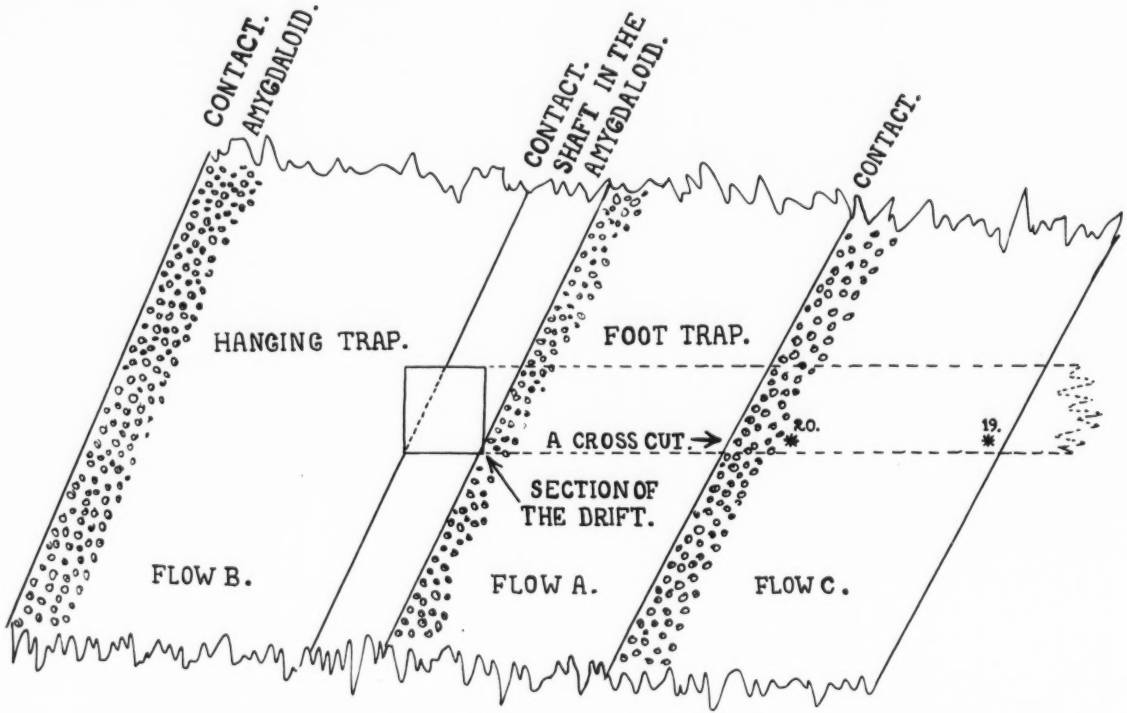


FIG. 2.—Enlarged cross-section of the flows.

C. Some flows intermediate between the middle and late flows.
D. Late Keweenawan flows as represented by the Quincy mine specimens and the Ashbed.

TABLE I.

1. A. The Champion Mine.

*Specimen No. 1.*—Shaft No. 4. Level No. 3. 310 feet vertically below the surface. A fine grained basalt five feet above the contact of the hanging trap.

$0.33 \times 10^{-13}$ gm. radium per gm. rock.

*Specimen No. 3.*—Shaft No. 1. Level No. 21. 2132 feet vertically below the surface. A fine grained basalt from the cross cut between the shaft and the drift, five feet above the contact of the hanging trap.

$0.90 \times 10^{-13}$ gm. radium per gm. rock.

*Specimen No. 5.*—Shaft No. 1. Level No. 38. 3728 feet vertically below the surface. A fine grained basalt from the cross cut between the shaft and the drift, five feet above the contact of the hanging trap.

$2.62 \times 10^{-13}$ gm. radium per gm. rock.

All the above specimens occur in the same flow, that immediately above the amygdaloidal lode being worked for copper in the Champion mine. The increase of activity with depth is worthy of note. Such a correlation also exists in the Calumet and Hecla district as shown below.

1. B. The Calumet and Hecla Mines.

*Specimen No. 9.*—Centennial shaft. Level No. 1. 114 feet vertically below the surface. A medium-fine grained basalt three feet above the contact of the hanging trap to the Kearsarge lode.

$0.71 \times 10^{-13}$ gm. radium per gm. rock.

*Specimen No. 12.*—Shaft No. 12. Level No. 78. 4702 feet vertically below the surface. A medium-fine grained basalt three feet above the contact of the hanging trap to the Kearsarge lode.

$4.16 \times 10^{-13}$ gm. radium per gm. rock.

*Specimen No. 13.*—Shaft No. 12. Level No. 78. Depth as in previous specimen. The Kearsarge amygdaloid lode. Specimen

sorted so that only original lava was obtained and the amygdaloidal material rejected.

$2.45 \times 10^{-13}$ gm. radium per gm. rock.

*Specimens Nos. 19 and 20.*—Shaft No. 12. Level No. 78. Depth as in previous specimen. These two specimens were taken from the bottom and near the top, respectively, of a thick ophite flow, the top of which is the Osceola amygdaloidal lode. In the cross cut from the Calumet and Hecla conglomerate to the Kearsarge lode. The "Draft mark" gives the distance along the horizontal cross cut, the angle of dip of this flow being 35°.

*Specimen No. 19.*—Draft mark 505 feet, or three feet above the bottom of the flow.

$0.57 \times 10^{-13}$ gm. radium per gm. rock.

*Specimen No. 20.*—Draft mark 275 feet or fifteen feet below the bottom of the amygdaloid and seventy-five feet along the cross cut from the top of the flow.

$0.74 \times 10^{-13}$ gm. radium per gm. rock.

Two points of interest are to be mentioned here. Comparing the results of specimen No. 12 and of specimen No. 19, both at approximately the same depth below the surface and from the bottom of basaltic flows, it is evident that the radioactive content may vary considerably from flow to flow. Moreover, comparing specimens Nos. 19 and 20, it is seen that the base of the flow is somewhat less active than near the top. This agrees with the idea that the more felspathic rocks are more radioactive since it has been pointed out that the upper parts of these lava flows tend to be more felspathic.[5]

That increase of basicity indicates a lower radium content is now generally accepted.

*Specimen No. 17.*—Shaft No. 12. Level No. 78. Depth as in previous specimen. A felsitic pebble from the Calumet and Hecla conglomerate taken about five feet from the bottom of the conglomerate.

$7.00 \times 10^{-13}$ gm. radium per gm. rock.

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[5] Powers, S., and Lane, A. C., Magmatic differentiation in effusive rocks. Bull. Amer. Inst. Mining Eng. (1916).

Lane, A. C., The Keweenaw series of Michigan. Mich. Geol. Survey, Ann. Report (1909), pp. 79–83, 658, 659, 739.

This specimen being felsitic follows the generalization mentioned above and is high in radium content compared to the basic flows.

### 1. C. Some flows intermediate between the middle and late flows.

These specimens are from the surface with the exception of specimen No. 25, which was from the Calumet and Hecla collection.

*Specimen No. 31.*—The Greenstone. A specimen from the quarry at the Phoenix mine, medium-fine grain in structure and about four feet from the bottom of the flow.

$0.88 \times 10^{-13}$ gm. radium per gm. rock.

*Specimen No. 29.*—The Greenstone. A specimen from above the North Cliff mine. A little coarser grain than specimen No. 31, and about 100 feet up in the flow.

$1.22 \times 10^{-13}$ gm. radium per gm. rock.

Again a decrease is to be noted in the radium content towards the bottom of the flow although the relative positions of the specimens with regard to the whole flow is less certain here than in the case of specimens Nos. 19 and 20.

*Specimen No. 25.*—The "Mesnard Epidote" which Lane[6] describes as a somewhat altered volcanic ash at the horizon of the Chippewa felsite. Tamarack mine. In the cross cut 500 feet vertically below the surface.

$4.71 \times 10^{-13}$ gm. radium per gm. rock.

### 1. D. The Quincy Mine and the Ashbed.

The Quincy mine specimens were not taken personally. With these specimens it is impossible to correlate the radium content so closely since the Pewabic amygdaloid lodes at the Quincy mines consist of a group of thin flows and the two specimens examined although forming the hanging trap to the lode worked in the respective levels may not be from the same flow.[7]

*Specimen No. 21.*—Shaft No. 2. Level No. 7. 370 feet vertically below the surface. A medium grained basalt about two feet above the contact of the hanging trap.

$1.18 \times 10^{-13}$ gm. radium per gm. rock.

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[6] Lane, A. C., *loc. cit.*, pp. 409, 436.

[7] See "Copper Deposits of Michigan", pp. 178–181.

*Specimen No. 23.*—Shaft No. 2. Level No. 91. 6182 feet vertically below the surface. A medium grained basalt about two feet above the contact of the hanging trap.

$0.70 \times 10^{-13}$ gm. radium per gm. rock.

The Owl creek riverbed specimen constitutes the geologically most recent flow examined and was a surface specimen.

*Specimen No. 28.*—A fine grained basalt one foot above the contact of the hanging trap to the ashbed amygdaloid.

$1.54 \times 10^{-13}$ gm. radium per gm. rock.

The foregoing results, not including the felsitic rocks, give an average of $1.29 \times 10^{-13}$ gm. radium per gm. of rock for the mean value of the plateau basalts as exemplified in the Keweenaw district. This result may be compared with the mean value of a very complete series by C. S. Piggot[8] for the volcanic Hawaiian lavas which showed on the average a radium content of $9.6 \times 10^{-13}$ gm. per gm. of sample. Although the plateau type might be expected to show lower values, this difference seems rather large. Piggot has pointed out, however, that these lavas may exhibit abnormality since they do not differ appreciably from the mean values of a long list of granites examined by him. On the other hand, the plateau basalts of the Keweenaw Point may be abnormally low and it is proposed in the near future to examine some similar plateau basaltic structure exercising the same precautions as were taken in sampling and determining the Keweenawan rocks. Against an abnormality of the Keweenaw basalts, however, can be quoted the results of V. S. Dubey's[9] determinations made in Professor Mache's laboratory in Vienna on three basic lavas of the Gwalior series in India.

TABLE II.

| | |
|---|---|
| Belaki-Bauri | $1.7 \times 10^{-13}$ gm. radium per gm. rock. |
| Santowa Temak | $1.8 \times 10^{-13}$ gm. radium per gm. rock. |
| Panier | $2.3 \times 10^{-13}$ gm. radium per gm. rock. |
| Mean | $1.9 \times 10^{-13}$ |

On collecting together the data for the surface specimens, or those nearest to the surface in mines where no surface specimens were taken, an apparently definite correlation was found between the

[8] C. S. Piggot, Amer. Journal Science, 22, July (1931).

[9] V. S. Dubey, Nature, 126, 807 (1930).

radium content and the time of laying down of the flow. Table III illustrates this correlation, the Champion mine hanging trap being the oldest determined and the following values falling in correct stratigraphical order, as reference to Figure 1 will show.

TABLE III.

| | | | |
|---|---|---|---|
| Specimen No. 1..... | Champion mine. | Level No. 3. | $0.33 \times 10^{-13}$ |
| Specimen No. 9..... | Centennial Shaft. | Level No. 1. | 0.71 |
| Specimen Nos. 31 and 29.... | Greenstone. | Surface. | 0.88 — 1.22 |
| Specimen No. 21..... | Quincy mine. | Level No. 7. | 1.18 |
| Specimen No. 28..... | Ashbed. | Surface. | 1.54 |

Whether such a correlation happens to be a coincidence or not will be determined when more of the intervening flows have been examined. It must be mentioned that Joly[10] has found a similar relation between the old and late eruptions of Vesuvius, although these are of the volcanic type as compared to the plateau basalts.

TABLE IV.

2. The Accessory Minerals.

The minerals examined are all closely connected with the copper and all contain copper either in the finely divided state or in chemical combination.

*Specimen No. 37.*—Copper Falls mine dump. Datolite. $H_2Ca_2B_2Si_2O_{10}$ from the Owl creek fissure. Containing microscopically disseminated native copper.

$1.10 \times 10^{-13}$ gm. radium per gm. mineral.

*Specimen No. 40.*—Ahmeek mine dump. Prehnite. $Al_2(SiO_4)_3Ca_2H_2$. Also containing disseminated copper.

$0.18 \times 10^{-13}$ gm. radium per gm. mineral.

*Specimen No. 38.*—Ahmeek mine. Algodonite. An arsenide of approximate constitution $Cu_6As$ as shown by rough analysis, from the Mohawk fissure.

$0.08 \times 10^{-13}$ gm. radium per gm. mineral.

*Specimen No. 38a.*—Ahmeek mine. Domeykite. An arsenide of approximate constitution $Cu_3As$ from the Mohawk fissure.

$0.13 \times 10^{-13}$ gm. radium per gm. mineral.

[10] J. Joly, Phil. Mag., 18, 577 (1909).

*Specimen No. 41.*—Baltic mine dump. Shaft No. 2. A copper sulphide. Chalcocite $Cu_2S$ from a fissure in the Baltic lode.

$0.10 \times 10^{-13}$ gm. radium per gm. mineral.

The determination of radium in the last four specimens above is accurate to only about 10% on account of the very small activity. All other results are accurate to about 3%.

The arsenides of the district have been studied in detail[11] and it seems that there is a definite order in the deposition of these minerals: Domeykite $Cu_3As$, Algodonite $Cu_6As$, Whitneyite $Cu_9As$ and native copper. Specimens Nos. 38 and 38a are of interest in that the radium content is almost directly proportional to the amount of arsenic in the mineral. This would show that in this type of progressive mineralization and probably in all mineralization in the district, the radium, or more correctly the parent element uranium, and its disintegration products,[12] tends to separate from the mineralizing solution in the company of other minerals than the native copper, which is in accord with the chemical viewpoint in that it is not to be expected that the salts of uranium and its disintegration products will pass through the same chemical processes that precipitate the copper in the form of metal. An extrapolation of the results for the arsenides to zero arsenic content, although very rough, shows that the copper should have a much smaller activity than can possibly be measured at present. Such has been found to be the case, in fact the native copper of the Keweenaw Point was the first specimen from this district to be examined. Paneth and Koeck[13] found less than the limit of detection corresponding to $<10^{-15}$ gm. per gm. of copper. This result has been checked in this research using 32.0 gms. of copper from the 91st level of the Quincy No. 2 Shaft.[14] The results of the determinations for two further specimens are given, the Duluth gabbro and a late granite. The Duluth gabbro, a hand specimen from out of the district, is of interest since it is considered

[11] T. M. Broderick, Economic Geology, 24, 2 (1929). See also "The Copper Deposits of Michigan," pp. 56–58.

[12] All the minerals and rocks of this district are definitely old enough to have allowed sufficient time for the establishment of radioactive equilibrium.

[13] Paneth and Koeck, loc. cit.

[14] Only two substances in the course of a prolonged series of studies on a variety of rocks and minerals, etc., have so far been found to contain radium in a smaller amount than can be detected by modern apparatus. In addition to the Keweenaw copper an iron meteorite, Savik, Greenland, contained $<2 \times 10^{-15}$ gm. per gm.

by some to be the source of the copper in the mineralizing solutions and as underlying the Keweenawan rocks. The late granite shows the higher radium content associated with felspathic rocks as compared to the basic basalts. These two are included in the summarizing Table V below.

TABLE V.

| Specimen No. | Description. | Type. | | Radium Content $\times 10^{13}$. | Calculated Uranium Content $\times 10^{7}$. |
|---|---|---|---|---|---|
| 1 | Champion mine. | Basalt. | | 0.33 | 0.97 |
| 3 | Champion mine. | Basalt. | | 0.90 | 2.65 |
| 5 | Champion mine. | Basalt. | | 2.62 | 7.71 |
| 9 | Calumet and Hecla mines. | Basalt. | | 0.71 | 2.09 |
| 12 | Calumet and Hecla mines. | Basalt. | | 4.16 | 12.23 |
| 13 | Calumet and Hecla mines. | Basalt. | | 2.45 | 7.21 |
| 19 | Calumet and Hecla mines. | Basalt. | | 0.57 | 1.68 |
| 20 | Calumet and Hecla mines. | Basalt. | | 0.74 | 2.18 |
| 31 | The Greenstone. | Basalt. | | 0.88 | 2.59 |
| 29 | The Greenstone. | Basalt. | | 1.22 | 3.59 |
| 21 | The Quincy mine. | Basalt. | | 1.18 | 3.47 |
| 23 | The Quincy mine. | Basalt. | 0.67 | | |
| | | | 0.65 | | |
| | | | 0.77 | 0.70 | 2.06 |
| 28 | The Ashbed. | Basalt. | | 1.54 | 4.53 |
| | Mean value. | Basalts. | | 1.29 | 3.79 |
| 17 | Calumet and Hecla mines. | Felsitic. | | 7.00 | 20.59 |
| 25 | Mesnard epidote. | Felsitic. | | 4.71 | 13.85 |
| 42 | A late granite. | Granitic. | | 4.21 | 12.38 |
| 43 | The Duluth Gabbro. | Gabbro. | | 0.69 | 2.03 |
| 37 | Datolite. | Silicate. | | 1.10 | 3.24 |
| 40 | Prehnite. | Silicate. | | 0.18 | 0.53 |
| 38 | Algodonite. Arsenide. | Copper mineral. | | 0.08 | 0.24 |
| 38a | Domeykite. Arsenide. | Copper mineral. | | 0.13 | 0.38 |
| 41 | Chalcocite. Sulphide. | Copper mineral. | | 0.10 | 0.29 |
| | Mean value. | Copper minerals. | | 0.10 | 0.29 |

The corresponding content in uranium has been inserted in column 5, using the equilibrium value of 1 gm. U = $3.4 \times 10^{-7}$ gm. Ra.

The author is especially indebted, to Dr. A. C. Lane, of Tufts College, Massachusetts, at whose instigation the work was commenced, to Professor Dr. F. Paneth, Koenigsberg, Germany, for placing the apparatus at his disposal and his help and guidance during the course of this re-

search, and to the American Academy of Arts and Sciences for a liberal grant in support of the research.

## Summary.

1. The distribution of radium in the Keweenawan rocks and minerals has been determined by analyses of a series of specimens from known locations and positions in the copper mines and basaltic flows of Keweenaw Point, Michigan.

2. Evidence of a correlation between the radium content and both depth and stratigraphical arrangement has been found.

3. An average value for the radium content of "Plateau Basalt" as exemplified by the Keweenawan flows is given.

4. There is evidence of a regular order in the radium content of the accessory minerals in the copper lodes according to the method of precipitation from the mineralizing solutions. More data are required on this point.

Baltimore, Maryland.
Koenigsberg, i. Pr. Germany.

# RADIOACTIVITY MEASUREMENTS.

## II. The Occurrence of Radium, Uranium and Potassium in the Earth.

By Wm. D. Urry.[1]

In this paper it is intended to give the most probable distribution of uranium and radium from the centre of the earth's core to the surface. Since it is impossible to make measurements beyond the very outermost of shells any computation of this distribution must be by comparison with material at hand. Such a procedure has been carried out by H. S. Washington[2] for the distribution of the elements throughout the earth. It was thought of interest to follow the postulate of this author more especially since similar general distributions are now widely accepted and the average radium content of the proposed constituent minerals and core has been determined of late by accurate measurements. Although the details vary somewhat between the various authors, it is perhaps best to follow the composition as given by Washington. For the purpose of completeness, Washington's Table I is reproduced here in part.

TABLE I.

Thickness and Mass of the Earth Shells.

| | Radial Thickness. | Mass. Metric Tons. |
|---|---|---|
| Central core | 3400 Kms. | $1.646 \times 10^{21}$ |
| Lithosporic shell | 700 | 0.513 " |
| Ferrosporic shell | 700 | 1.360 " |
| Peridotitic shell | 1540 | 2.417 " |
| Basaltic shell | 40 | 0.065 " |
| Granitic shell | 20 | 0.029 " |
| Whole earth | 6400 | $6.030 \times 10^{21}$ |

The composition of the central core was assumed to be that of the average of 318 iron meteorites. The average radium content of 22 iron meteorites, all included in the above 318, as determined by

[1] Contribution from the Research Laboratory of Physical Chemistry, Massachusetts Institute of Technology. No. 302.

[2] H. S. Washington, Amer. Journal Science, IX, May (1925).

Paneth and Koeck,[3] was found to be about $2.5 \times 10^{-14}$ gm. radium per gm. of meteorite.[4]

Washington assumed that the material of the lithosporic shell is composed of equal weights of nickel-iron and olivine in analogy to the stony-iron or pallasitic meteorites. The ferrosporic shell he took to be comparable to the stony chondritic meteorites. The best radium determination for these meteorites is again probably that by Paneth and Koeck[5] on a composite sample of equal parts by weight of twenty chondritic meteorites supplied by Professor Dr. G. v. Hevesy.[6] The radium determination gave $12 \times 10^{-14}$ gm. per gm. The average content of the pallasites can now be calculated from the chondritic average and the iron meteorite average to be about $7 \times 10^{-14}$ gm. per gm.

For the composition of the peridotitic shell the average of twenty analyses of achondritic stony meteorites was calculated. There is no radium determination of a composite of these stony meteorites nor sufficient single analyses to give a mean value. For the lower basaltic shell the composition of Daly's[7] average basalt was used. Table II gives the mean values of radium determinations by several workers. The final value is derived by weighting the determinations in preference to averaging the means as given by each author. A mean value given by Joly is excluded since he has included with the basalts: gabbros, diabases and norites.

The granitic shell was calculated from the "Average Igneous Rock" analyses. Paneth and Koeck[8] have also determined the radium content of a composite sample of 282 rocks prepared by Hevesy.[9] The sample includes equal parts by weight of 133 granites, 9 quartz diorites, 35 diorites, 82 gabbros and norites and 23 ultrabasic rocks. The presence of the ultrabasic rocks will lower the mean value somewhat but on the other hand a certain percentage of this

[3] F. Paneth and W. Koeck, Zeit. Physik. Chemie. Bodenstein-Festband 145 (1931).

[4] Bulletin No. 80, National Research Council, Washington, D. C., p. 416. A. Holmes gives $3.6 \times 10^{-14}$ gm. per gm. including Toluca. Since the latest measurements on this meteorite are still in doubt, it has not been included in the average given above.

[5] Paneth and Koeck, *loc. cit.*

[6] G. v. Hevesy, E. Alexander and K. Wuerstlin, Z. Anorg. Ch. 194, 316 (1930).

[7] Daly, Igneous Rocks (1914), 27, No. 53.

[8] Paneth and Koeck, *loc. cit.*

[9] Hevesy, Alexander and Wuerstlin, *loc. cit.*

TABLE II.

| Location. | Observer. | No. of specimens. | Ra. in gm. per gm. of rock. |
|---|---|---|---|
| Basalt. Ireland. | Strutt.[1] | 1 | $55 \times 10^{-14}$ |
| Basic rocks. Various. | Strutt.[2] | 11 | 53 " |
| Basic rocks. (Archean.) Mysore State. India. | Smeeth and Watson.[3] | 21 | 24 " |
| Basalts. England. | Strutt.[4] | 4 | 37 " |
| Basalt. Deccan trap. India. | Dubey.[5] | 1 | 45 " |
| Gwalior basalts. India. | Dubey.[6] | 3 | 19 " |
| Keweenaw basalts. Michigan, U. S. A. | Urry.[7] | 15 | 13 " |
| | Mean value. | 56 | $28 \times 10^{-14}$ |

[1] Strutt, R. J., Proc. Roy. Soc. London, A. 80, 586 (1908).
[2] Strutt, R. J., Proc. Roy. Soc. London, A. 77, 472 (1906).
[3] Smeeth and Watson, Phil. Mag., 6, 35, 206 (1918).
[4] Strutt, R. J., Proc. Roy. Soc. London, A. 84, 377 (1910).
[5] Dubey, V. S., Bull. No. 80, National Research Council, Washington, D. C.
[6] Dubey, V. S., Nature, 126, 807 (1930).
[7] Urry, W. D. See the foregoing publication.

type will be present in the granitic layer. The determination gave $128 \times 10^{-14}$ gm. per gm. rock. An average value for the radium content of igneous rocks from different parts of the world is given by Strutt as $170 \times 10^{-14}$ gm. per gm.[10]

Piggot[11] has determined the radium content of a series of granites from Georgia to Greenland, including some gabbros and schists. The average of sixteen locations with about 100 determinations is given as $90 \times 10^{-14}$ gm. per gm. With due regard to the above mentioned average values and on selection of the most probable results from a very complete table by G. S. Rogers,[12] the average content of the igneous rocks is taken as about $140 \times 10^{-14}$.

In figure 1 the radium content of the various shells of the earth as postulated by Washington is plotted against depth, the average

[10] Strutt, R. J., Proc. Roy. Soc. London, A. 77, 472 (1906) and A. 78, 150 (1906). The above value is that corrected by Eve and McIntosh, Phil. Mag. 6, 14, 231 (1907) for the use of an erroneous constant.
[11] Piggot, C. S., Amer. Journal Science, 21, Jan. (1931).
[12] G. S. Rogers, U. S. Geological Survey, Professional Paper 121, "Helium bearing natural gas."

content for any given shell being plotted against the depth to the middle point of that shell. On the same figure is plotted the potassium content as given by Washington also expressed in gm. per gm. Table III gives the complete data including the total radium, uranium and potassium content of each shell and the helium produced annually.

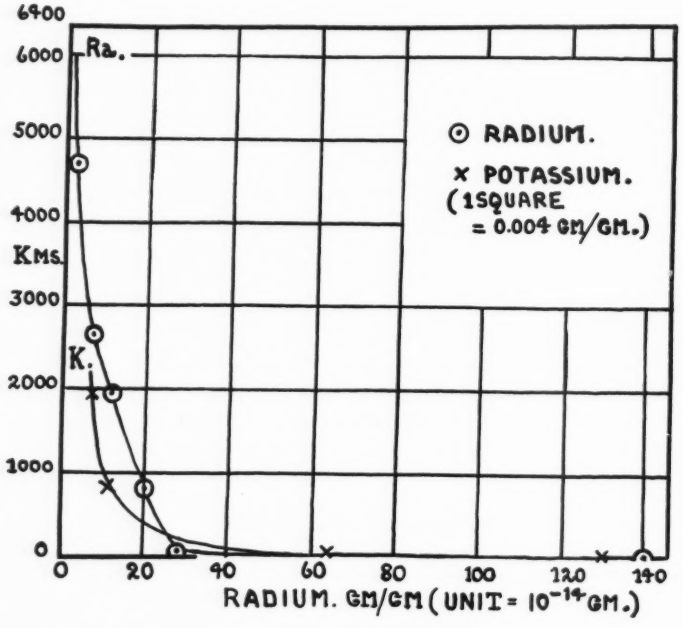


FIG. 1.—Variation of Radium and Potassium Content with depth.

By far the greatest concentration of the radium and potassium on reference to columns 3 and 8 is found to be in the uppermost thirty kilometers of the earth's surface. Unfortunately reliable thorium results sufficient in number to calculate mean values are not at hand.

That the radioactivity must fall off very appreciably with depth has been inferred in all calculations based on the hypothesis of a cooling earth. Since older computations of the average radioactivity of the outer shells have led to higher values than given here

TABLE III.

| | Radial thickness. | Depth to middle of shell. | Radium. | Uranium. | Total Radium in shell. | Total Uranium in shell. | Helium produced annually. | Potassium. | Total Potassium in shell. |
|---|---|---|---|---|---|---|---|---|---|
| | Kms. | Kms. | Gm./gm. | Gm./gm. | Metric tons. | | Cu. meters. | Gm./gm. | Met. tons. |
| Central Core..... | 3400 | 4700 | $2.5\times10^{-14}$ | $0.74\times10^{-7}$ | $411\times10^{5}$ | $1233\times10^{11}$ | $14.30\times10^{6}$ | .... | .... |
| Lithosporic Shell.. | 700 | 2650 | 7.0 | 2.06 | 359 | 1077 | 12.41 | .... | .... |
| Ferrosporic Shell.. | 700 | 1950 | 12.0 | 3.53 | 1632 | 4896 | 56.78 | 0.0014 | $1903\times10^{15}$ |
| Peridotitic Shell .. | 1540 | 830 | (20) | 5.88 | 4834 | 14502 | 168.19 | 0.0022 | 5317 |
| Basaltic Shell..... | 40 | 40 | 28 | 8.24 | 182 | 546 | 6.33 | 0.0128 | 832 |
| Granitic Shell .... | 20 | 10 | 140 | 41.18 | 406 | 1218 | 14.13 | 0.0260 | 754 |
| Whole Earth..... | 6400 | | | | 7824 | 23472 | 272.14 | | 8806 |

it has often been necessary to postulate the existence of radioactive elements for only a few kilometers depth. Holmes[13] who has criticized such a complete removal of radioactive elements from the lower shells gives a value of 60 calories/sq. cm. as the annual heat loss by conduction to the surface and radiation into space. By taking most probable values for a thorium content of the three outer shells, values which however are not at all final, it is possible, in combination with the above values for radium and potassium, to calculate roughly the depth required to offset the above loss. Table IV sets out the various heat quantities required to be known.

TABLE IV.

| | | | |
|---|---|---|---|
| Granitic shell. | 20 kms. thick. | Uranium heating effect. | 18.2 Cals/sq.cm. |
| | | Potassium heating effect. | 1.7 Cals/sq.cm. |
| Basaltic shell. | 40 kms. thick. | Uranium heating effect. | 7.3 Cals/sq.cm. |
| | | Potassium heating effect. | 1.7 Cals/sq.cm. |
| Total radium and potassium heating effect—both shells | | | 28.9 Cals/sq.cm. |
| Taking a thorium content for the granitic shell of $10^{-5}$ gm. per gm. rock. | | Thorium heating effect | 12.9 Cals/sq.cm. |
| Taking a thorium content for the basaltic shell of $2 \times 10^{-6}$ gm. per gm. rock. | | Thorium heating effect | 5.2 Cals/sq.cm. |
| | | Total thorium heating effect of both shells | 18.1 Cals/sq.cm. |

Thus the sum total heating effect of the radioactivity in both shells of 47 cals/sq. cm. is 13 cals/sq. cm. less than the loss by radiation from the earth's surface. Assuming a thorium content of $1 \times 10^{-6}$ gm. per gm. for the peridotitic shell, the total uranium, thorium and potassium heating effect per sq. cm. per cm. depth for this shell is $2 \times 10^{-6}$ cals/sq. cm. and hence the remaining 13 cals would be supplied by a depth of 65 kilometers of the peridotitic shell. Even taking somewhat larger values for the thorium content the heat required to counterbalance the loss of 60 cals/sq. cm. annually would correspond to a depth reaching into the upper part of the peridotitic shell. This is in good accord with the postulates necessary in supporting Holmes's theory of convection currents in the substratum.[14]

Columns 4 and 6 give the uranium content of the earth calculated on the basis that in radioactive equilibrium the ratio of uranium

[13] Holmes, A., Radioactivity and Earth Movements, Trans. Geol. Soc. Glasgow, XVIII, Part III (1928–29).

[14] Holmes, A., *loc. cit.*

to radium is 1 to $3.4 \times 10^{-7}$. The annual production of helium is calculated on the basis that 1 gm. uranium in equilibrium with all its disintegration products yields $1.16 \times 10^{-7}$ cc. annually. A yearly loss of about 0.4% of the helium generated annually in the granitic shell would suffice in $1000 \times 10^6$ years to give the total helium in the atmosphere as calculated by Van Orstrand[15] to be about $58 \times 10^{12}$ cubic meters. The average surface denudation since the close of the pre-cambrian times, even allowing that only a fraction of the helium is lost on denudation, is more than sufficient to produce the total atmospheric helium. One important determination, however, bearing on this question, namely, the distribution of helium between the atmosphere and the oceanic waters, will be made in the near future. It is thought that such a determination will account at least in part for the apparently large excess of helium freed in geological time over the amount existing in the atmosphere at present.

## Summary.

1. A probable distribution of the radium and uranium throughout the earth is given basing the computations on Washington's proposed mineralogical and chemical structure and using the latest determinations for composite samples and analytical series.

2. The results show a considerably lower mean uranium content than has usually been adopted for the three outer shells and excludes the possibility of a complete concentration into the upper two shells, a conclusion that is in good agreement with Holmes' theory of convection currents in the substratum.

## General References.

[16] Holmes, A., Radioactivity and the earth's thermal history.
Part I. The concentration of the radioactive elements in the earth's crust. Geol. Mag., 6, 2, 60 (1915).
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[17] Jeffreys, H., The Earth's Thermal History, Geol. Mag., 64, 444 (1927).
The Earth. 2d edition. Cambridge University Press (1929).

[15] See "Helium bearing natural gas," same as footnote 12.

[18] Clarke, F. W., The evolution and disintegration of matter. U. S. Geological Survey, Professional Paper 132 D (1924).

[19] Humphreys, The Physics of the Air. Philadelphia (1920).

[20] Daly, R. A., Our mobile Earth. New York (1926).

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